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Multigenerational performance development of male and female top-elite swimmers–A global study of the 100 m freestyle event

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Background: The present study investigated longitudinally the performance development of a multigenerational sample of competitive swimmers. The aim of the study was to provide unique insight into the junior toward senior performance development of those few who reached top-elite level. Season Best Times (SBT) of 100 m freestyle performance of international swimmers, (1.305 males, aged 12-26 and 1.841 females, aged 12-24) competing in at least five seasons between 1993 and 2018, were corrected for the prevailing world record (WR). Swim performance was defined as a relative measure: relative Season Best Time=(SBT/WR) × 100. Based on rSBT, four performance groups were defined: top-elite, elite, sub-elite, and high-competitive.
Results: Univariate analyses of variance showed that male top-elite swimmers outperformed high-competitive swimmers from the age of 12, sub-elite swimmers from the age of 14 and elite swimmers from the age of 18 while female top-elite swimmers outperformed high-competitive and sub-elite swimmers from the age of 12 and elite swimmers from the age of 14 ($P < .05$). Frequency analysis showed that male top-elite swimmers for the first time achieved top-elite level between the 17 and 24 years old (mean age of 21) while female top-elite swimmers started to perform at top-elite level between the 14 and 24 years old (mean age of 18).
Conclusion: Male and female top-elite swimmers are characterized by a high-performance level from 12 years on and progressively outperform swimmers from similar age. However, this goes together with a large variety in the individual pathways toward top-elite level within and between sexes.

KEYWORDS
acquisition of expertise, competitive swimming, sport performance, talent, world record

1 | INTRODUCTION

In the context of athlete development, the increase of sport performance of a youth athlete aiming to make it to the top is key.[1] In a relatively short time, young athletes will have to continue improving their sport performance to reach excellence.[1-3] Knowledge about general performance development of those who have made it to the top could provide important information for athletes, coaches, and federations.[4] A thorough understanding of performance development during an athlete's career could facilitate the identification and development of talented athletes and could enable sport federations to target their support toward those athletes who have the greatest potential to make it to the top.[5]

A fitting sport to investigate the performance development of youth athletes on their way to the top is competitive swimming. Competitive swimming is a time-trial sport in which a swimmer tries to travel a certain distance in the water as fast as possible. It is a popular global sport with a high level of competition in which the gap between the gold medalist and the last finisher in international competition is constantly decreasing.[6] The key distance in competitive swimming is the 100 m freestyle long course event, which has been on every Olympic program since 1904 (men) and 1912 (women). In this event, competition starts from an early age on and the competition level is high for both male and female swimmers.[7,8] Due to technological progressions like electronic timekeeping and online accessible repeated-measures competition data, retrospective studies on performance data of swimmers in the 100 m freestyle event offer great opportunities to provide new insights for performance development in competitive swimming.

The time-captured nature of competitive swimming comes with a strong emphasis on swim performance from a young age on. In practice, this is marked by the early selection of the fastest youth swimmers into athlete development programs based on their competitive performance times.[9] The underlying assumption behind this approach is that future winners can be identified on the basis of their junior swim performance.[10] In this way, swim performance from a young age on is highly valued and considered as a serious predictor of success.[9]

Nevertheless, the utility of talent identification on the basis of performance at early ages has been questioned by several researchers.[3,11-13] Specific for competitive swimming, research from Barreiros and colleagues[14] has shown that the conversion rates of junior elite swimmers into senior elite swimmers are generally low. Moreover, one of the concerns of using this approach is the fixed focus on the swimmer's current performance level rather than the swimmer's potential performance level. This risks the exclusion of talented swimmers who may not be the fastest yet, but who may be so in the future.[3,15] Scientific-based knowledge about the general performance development of top-elite swimmers throughout their entire career may enlighten the value of this approach.

Research on adult elite swimmers has given valuable insight into performance progression and the age of peak performance. The study of Pyne and colleagues[16] showed that performance progression by ~1.0% within a competition and ~1.0% within the year leading up to the Olympics is necessary to stay in contention for a medal at the Olympic Games. Allen and colleagues [4,17] modeled the career performances of Olympic top-16 swimmers and concluded that elite male swimmers achieve their peak performance at ~24 (± 2) years while elite female swimmers achieve peak performance at ~22 (± 2) years. The difference in age of peak performance between sexes can presumably be explained by the in general ~2-year earlier onset of puberty in females compared with males.[18] Given this information, a comparison of the performance development between young male and female swimmers is of considerable interest as differences in performance development between sexes may hold important implications for training and athlete development programs. Both aforementioned studies provide valuable information about performance development of senior elite swimmers during adulthood, however, insight regarding the performance development during their younger years relative to swimmers who did not reach elite level is lacking. Big data analyses over multiple generations could provide relevant information about how elite swimmers got to their high level of expertise. What characterizes their successful performance development over the years compared to those who did not make it to the top?

The present study investigates the 100 m freestyle performance development of a multigenerational sample of swimmers in order to provide more insight into the junior toward senior performance development of those few who reached top-elite level. Each research question is answered separately for male and female swimmers. The research questions we aim to answer are as follows: (a) From which age on do top-elite swimmers outperform swimmers from other performance groups (i.e., high-competitive, sub-elite, and elite)? (b) From which age on do top-elite swimmers start to perform at high-competitive level, sub-elite level, elite level, and top-elite level? The results of this study add value to both science and sport practice as it broadens the knowledge about general performance development of top-elite swimmers. It may function as a guideline for athlete development programs by providing scientific-based knowledge about the performance development of top-elite swimmers.

2 | METHODS

2.1 | Ethical approval

All procedures used in the study were approved by the Local Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (201900334) in the spirit of the Helsinki Declaration with a waiver of the requirement for informed consent of the participants given the fact that the study involved the analysis of publicly available data.

2.2 | Data collection

The swimmers we selected for this study were international male and female swimmers with performance data on the 100 m freestyle long course event. Performance data were obtained from Swimrankings,[7] a recognized public data source which records swimming race results. Performance data were collected from 113 countries across different parts of the world including Africa, America, Asia, Australia, and Europe. We collected all available 100 m freestyle long course results from Swimrankings' database, which initially resulted in 2.683.412 observations between 1993 and 2018.

2.3 | Data processing

Performance data from the 1st of January 2008 till the 1st of January 2010 were excluded from analysis. During that time, swimmers were allowed to wear newly introduced full-body polyurethane swimsuits which led to a major benefit of the swimmers' drag force reduction.[19-21] From the 1st of January 2010 onwards, FINA banned these suits. Swim performances over 180 seconds were excluded from analysis to ensure a representative dataset. A total of 2.383.616 observations were remained.

Based on swim dates, performance data were classified in swimming seasons. Each swimming season officially starts on the first of September of a calendar year and ends on the 31st of August of the next calendar year (1st of September 2018 till 31st of August 2019 corresponds to swimming season 2018/2019). Swimmers were classified in age categories based on their age on the 31st of December of the swimming season (a girl who is 14 years old on the 31st of December 2018 would be classified in age category 14 year for swimming season 2018/2019). Therefore, all ages mentioned in the present study refer to the age category in which a swimmer participated during the swimming season and not the calendar age of the swimmer. For each swimmer, we selected one Season Best Time (SBT) per swimming season which we used for further analysis. A total of 1.131.963 observations were remained.

2.4 | Inclusion criteria

For the purpose of this study, it is important to outline the individual performance development from a young age on toward the adult age of peak performance (or beyond). Therefore, only those swimmers who; (a) were between 12 and 24 years old (female) or between 12 and 26 years (male) old; (b) were in competition for at least five seasons; (c) had at least one SBT within the age category of 16 years or younger; and (d) had at least one SBT within the age category of 20 years (female) or 22 years (male) or older were included.[4,17] This resulted in 5.636 individual swimmers (3.259 female, 2.377 male) with 40.063 SBTs (22.239 female and 17.824 male) with an average of 7.6 ± 2.1 observations per swimmer.

2.5 | Defining swim performance and performance development

The present study includes swim performances of multiple generations, necessitating the correction of evolution in a given sport.[22] The continuous increase in world-class performances at Olympic Games and World Championships clearly reflects the evolution in a sport, as well as the improvement of world records.[6,23] For example, at the 100 m freestyle event, the world record for females has been improved from 54.48 seconds to 51.71 seconds with 2.9 seconds (~5.3%) from 1994 to 2017[8] and for males from 48.42 seconds to 47.04 seconds (fastest time in textile) with 1.38 seconds (~2.9%).

To correct for evolution in competitive swimming, we use a method to compare performance over multiple generations, introduced and validated by Stoter and colleagues.[22] First, each swimmer's SBT per swimming season between 2018 and their earliest available competitive performance was determined. Second, SBTs were related to the prevailing world record (WR) or the fastest time in textile of the corresponding sex. The prevailing WR is the official WR at the date the athlete swam the SBT. WRs from 2008 to 2009 were replaced by the prevailing fastest time in textile. The corrected SBT will be referred to as relative Season Best Time (rSBT) and is presented as a percentage of the world record or fastest time in textile. In this study, rSBT defines swim performance (see Equation 1).

$$\text{rSBT} = \left(\frac{\text{SBT}}{\text{WR}}\right) \times 100\% \quad (1)$$

2.6 | Defining performance levels and groups

Four performance levels were defined; top-elite, elite, sub-elite, and high-competitive. Each performance level was characterized by sex-specific limits to account for differences in competition level between males and females (Table 1). The limits were calculated as the mean of 5 rSBTs for the xth swimmer from either the 100 m freestyle performance FINA World Ranking Lists of 2014-2018 [18] or the 100 m freestyle performance National Ranking Lists of the Netherlands

TABLE 1 Limits of performance levels for males and females separately

Performance level	Males	Females
Top-elite	rSBT < 102,2%	rSBT < 102,8%
Elite	102,2% <> rSBT < 104,0%	102,8% <> rSBT < 105,5%
Sub-elite	104,0% <> rSBT < 107,9%	105,5% <> rSBT < 108,0%
High-competitive	107,9% <> rSBT < 114,1%	108,0% <> rSBT < 114,6%

2014-2018 [12]. The limits of the top-elite performance level were based on rSBTs of the 8th male and female swimmer of the FINA World Ranking List 2014-2018 (e.g., rSBT 8th male swimmer 2014 + rSBT 8th male swimmer 2015 + rSBT 8th male swimmer 2016 + rSBT 8th male swimmer 2017 + rSBT 8th male swimmer 2018/ 5). The other limits were defined so that they represented the 50th male and female swimmer of the FINA World Ranking List 2018 (elite performance level) and the 8th and 50th male and female swimmer of the National Ranking List of the Netherlands of 2018 (sub-elite and high-competitive performance levels, respectively).

We determined each swimmer's current performance group by allocating the rSBT of a given season to one of the four performance levels. For example, if a 16-year-old boy has a rSBT of 108%, his current performance level corresponds with the limits of the high-competitive performance group. Next, we determined each swimmer's best performance group by allocating the best rSBT ever to one of the four performance levels, meaning that a swimmer either once or multiple times has reached this performance level at any age. For example, if a boy has a best rSBT ever of 105%, his best performance level corresponds with the limits of the sub-elite performance group. A swimmer's current performance group is a dynamic variable and may change over time, whereas a swimmer's best performance group remains static. Swimmers with a best rSBT ever outside the limits of the high-competitive level (best rSBT > 114.1% for males and best rSBT > 114.6% for females) were excluded from further analysis (a total of 16.406 observations). Moreover, outliers were excluded (a total of 647 observations) using stem-and-leaf plot, as swimmers might have a poor season due to injury, illness or other reasons, which are not representative for the swim performance of swimmers in the corresponding performance group. Table 2 presents the male/female distribution and the number of observations (i.e., rSBTs per swimming season) for each performance group included for the analysis on swim performance.

2.7 | Defining first entry ages

For top-elite swimmers only, we determined the first entry age of each performance level. The first entry age is the minimum age at which a swimmer for the first time achieved a higher performance level (eg, performance level transition from sub-elite level to elite level). First entry ages for skipped performance levels (e.g., a performance level transition from sub-elite level to top-elite level) were not reported.

2.8 | Statistical analysis

All data were analyzed for male and female swimmers separately using IBM SPSS Statistics 24 and R. Mean scores and standard deviations were calculated for swim performance (rSBT) for the four performance groups per age category. Per age category, a one-way independent analysis of variance (ANOVA) was used to examine group differences based on rSBT with performance group as independent variable. Planned contrasts were performed to determine differences between top-elite swimmers and swimmers of other performance groups per age category. A frequency analysis with first entry age as variable was executed for top-elite swimmers only. Mean scores and frequency distribution tables of first entry age were produced for the four performance levels (high-competitive level, sub-elite level, elite level, and top-elite level). Statistical tests were executed for the age categories in which there were more than two observations in the top-elite performance group. For all tests, $P < .05$ was set as significance.

3 | RESULTS

3.1 | Differences in swim performance between top-elite swimmers and other performance groups

Figure 1 illustrates the performance development of male and female swimmers on the 100 m freestyle from age 12 to 26 (males) and 12 to 24 (females) specified for each of the four performance groups.

For males, there was a significant effect of best performance group on rSBT from age 12 till 26 ($P < .05$). Planned comparisons between the top-elite performance group and other performance groups revealed that from the age of 12, top-elite swimmers performed better than high-competitive swimmers ($t(273) = -2.643$, $P = .009$). From the age of 14, top-elite swimmers performed better than sub-elite swimmers ($t(6.169) = -3.516$, $P = .012$). From the age of 18, top-elite swimmers performed better than elite swimmers ($t(909) = -2.051$, $P = .041$).

For females, there was a significant effect of best performance group on rSBT from age 12 till 24 ($P < .05$). Planned comparisons between the top-elite performance group and other performance groups revealed that from the age of 12, top-elite swimmers performed better high-competitive swimmers ($t(430) = -4.034$, $P < .001$) and sub-elite ($t(430) = -2.268$, $P = .024$). From the age of 14, top-elite swimmers performed better than elite swimmers ($t(939) = -3.574$, $P < .001$).

3.2 | The stages toward acquisition of top-elite performance level

Figure 2 shows the first entry age per performance level of male and female top-elite swimmers. In other words, it

TABLE 2 Total number of swimmers (N = 3.146) and observations (N = 23.010) for each performance group for the analysis on swim performance (rSBT)

	Males		Females	
	Individuals	*Observations*	*Individuals*	*Observations*
Top-elite	29	274	57	504
Elite	62	582	218	1.734
Sub-elite	394	3.265	378	2.786
High-competitive	820	6.059	1.188	7.806
Total	1.305	10.180	1.841	12.830

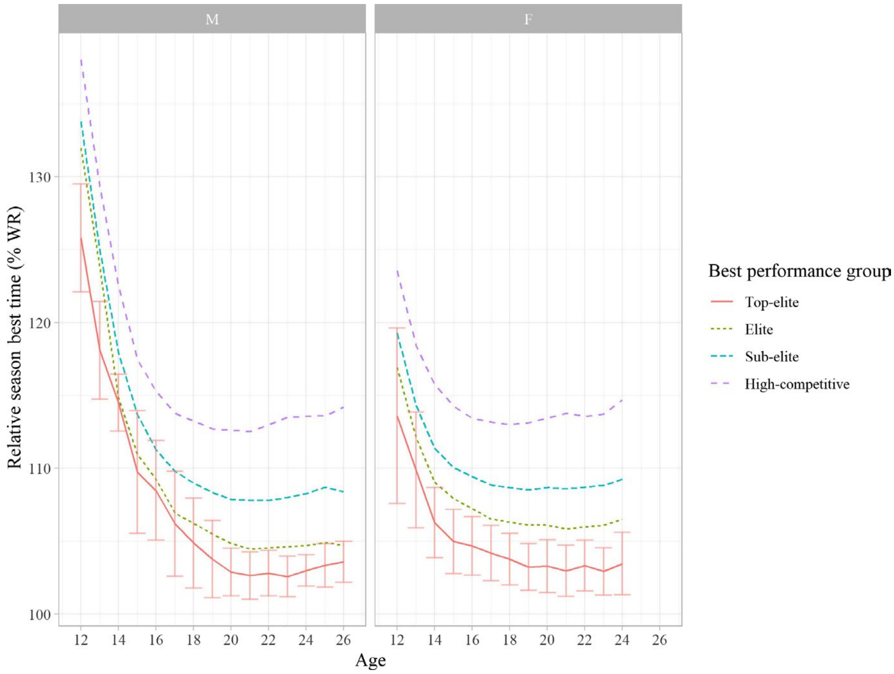

FIGURE 1 Performance development of male (left) and female (right) swimmers on the 100 m freestyle from age 12 to 26 specified for each of the four best performance groups

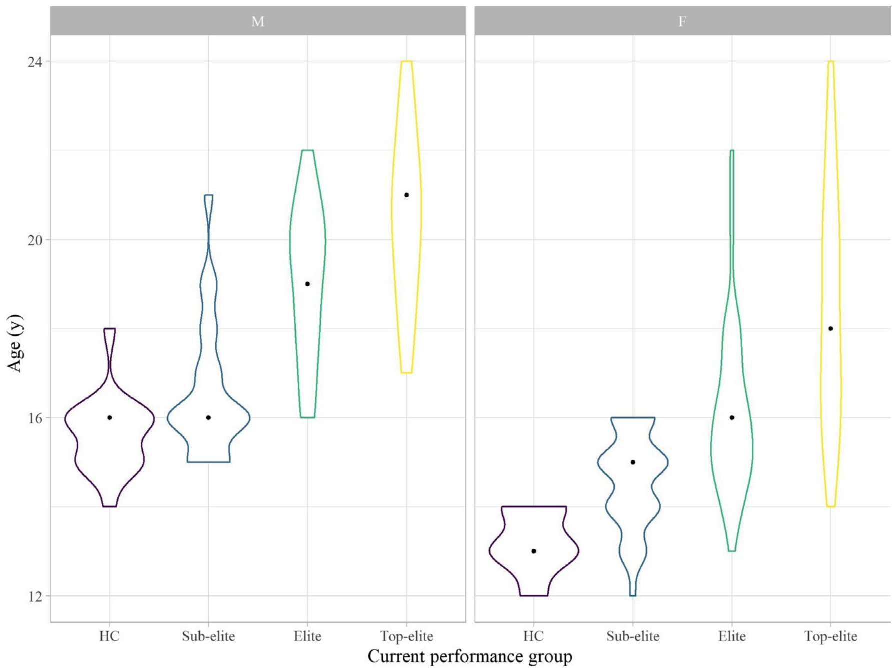

FIGURE 2 The distribution in age categories at which male (N = 29) and female (N = 57) top-elite swimmers for the first time performed at high-competitive (HC), sub-elite, elite and top-elite level. Dots represent mean ages

presents the distribution in age categories at which male and female top-elite swimmers for the first time performed high-competitive, sub-elite, elite, and top-elite level.

For males, the first entry age in high-competitive level ranges between 14 and 18 years, in which the majority of the male top-elite swimmers entered high-competitive level at the age of 16. The first entry age of sub-elite level ranges between the 15 and 21 years. At least one male swimmer who reached top-elite level, started participating at the sub-elite level for the very first time at the age of 15, while at least one other top-elite swimmer was 21. The age ranges of sub-elite level are largely similar to the age ranges at elite level, however, the age at which the majority of male top-elite swimmers started to perform at elite level (20 years) is fairly higher than the age at which the majority of male top-elite swimmers started to perform at sub-elite and high-competitive level (both 16 years). Top-elite level performances started from the age of 17 years on, in which at least one male swimmer entered top-elite level for the first time at 24 years old. The majority of males entered top-elite level around the age of 21.

For females, the first entry age in high-competitive level ranges between the 12 and 14 years, in which the majority of female top-elite swimmers entered high-competitive level at the age of 13. This is about three years earlier than their male counterparts. The first age of sub-elite level ranges between the 12 and 16 years. The majority of the female top-elite swimmers reached sub-elite level for the first time when they were 15 years. The first female top-elite swimmer entered elite level when she was 13 years, however, the majority started to perform at elite level at the age of 15. As in male top-elite swimmers, at least one female top-elite swimmer reached elite level when she was 22 years. The range of first entry ages in female top-elite swimmers is widely spread at top-elite level. The first female top-elite level swimmer who entered top-elite level was only 14 years, however, at least one female top-elite swimmer reached elite level when she was 24 years. In between, no clear pattern was found for the majority of the swimmers.

4 | DISCUSSION

The present study investigated the 100 m freestyle performance development longitudinally (over at least 5 years) in a multigenerational (over more than 20 years) sample of competitive swimmers to provide unique insight into the junior toward senior performance development of those few who reached top-elite level. The main findings showed that (a) from 12 years on, top-elite swimmers progressively outperformed swimmers of similar age, and that (b) there is a wide variety in the age at which male and female top-elite swimmers start to perform at high-competitive, sub-elite, elite and top-elite level.

The findings of the present study concretize that successful performance development to the top is characterized by a high level of expertise from 12 years on. Male top-elite swimmers outperformed high-competitive swimmers from 12 years on, sub-elite swimmers from 14 years on and elite swimmers from 18 years, while female top-elite swimmers outperformed high-competitive and sub-elite swimmers from 12 years on and elite swimmers from 14 years on. This progressive trend not only characterizes the differences between performance groups, but also the variety within the top-elite performance group. For both male and female top-elite swimmers, it seems that the higher the performance level becomes, the more variety in the first entry age range exists. For example in female top-elite swimmers, the first entry age range expanded from two years (12-14 years) in high-competitive level to ten years (14-24 years) at top-elite level. This means that at least one 14-year-old female top-elite swimmer entered high-competitive level while at least one other female top-elite swimmer achieved at the same age top-elite level. Looking at the differences between male and female top-elite swimmers, we see that most of the female top-elite swimmers achieved the high-competitive, sub-elite, elite, and top-elite level at a younger age compared with most of the male top-elite swimmers. For example, most female top-elite swimmers reached high-competitive level at the age of 13 while most male top-elite swimmers reached high-competitive level at the age of 16. Together, these results point out crucial differences in the individual pathways of performance development toward top-elite level within and between male and female swimmers.

Now, an intriguing question is which underlying performance characteristics (e.g., anthropometrical, technical, tactical, physiological, and psychological characteristics) contribute to the successful performance development toward top-elite level. In here, it is important to consider that the underlying performance characteristics are influenced by maturation, learning, and training [24-26] and that athletes always develop in and with their environment. The environment (e.g., parents, coaches, talent development programs, competition, and training facilities) plays a crucial role in developing the underlying performance characteristics.[27,28] For example, the popularity of a sport might influence national, regional, and local selection procedures for talent identification and development programs and the level of competition. Individual differences in underlying performance characteristics, environmental characteristics, timing, and tempo of the growth spurt and the number and quality of training hours may harness possible explanations for differences in swim performance between performance groups and sexes and for the wide variation in developmental patterns between top-elite swimmers. Therefore, future, longitudinal studies following youth swimmers throughout their sports career, measuring underlying performance characteristics, mapping environmental characteristics and tracking their maturation, learning, training, and level of swim performance, could potentially provide further insight into successful 100 m freestyle performance development of top-elite swimmers.[3,29] In here, the effect of age of selection on the performance development of those reaching top-elite level should be addressed as well.

The present study is the first that investigated 100 m freestyle performance development at such large scale. Following the method developed by Stoter and colleagues,[22] the present study defined swim performance as a relative measure instead of an absolute measure. The major strength of using a relative measure of swim performance (rSBT) is that it allows a more "fair" comparison of swim performance between and within swimmers. Therefore, we were able to include swim performance over multiple generations which resulted in a big data set with multigenerational and longitudinal data. Consequently, we extended group sizes of populations characterized with smaller sample sizes (eg, top-elite swimmers). This provided us the unique opportunity to investigate 100 m freestyle performance development of top-elite, elite, sub-elite, and high-competitive swimmers over more than 20 years. In a similar way, other sports with absolute performance measures (i.e., time-trial sports such as cycling or running) can be studied. However, when applying this method it is important to realize that a different classification of performance groups may lead to different outcomes.[30] Hence, the present study carefully considered the definitions of top-elite, elite, sub-elite, and high-competitive swimmers and defined performance groups based on task- and sex-specific limits, meaningful for the sport for competitive swimming.

With particular interest, the present study researched the performance development of top-elite swimmers. In here, the sport science perspective of striving to find regularities and patterns that can be applied to a whole population [31] was mixed with the investigation of individual pathways, a highly relevant and valuable combination for research in elite sports since experts in sports are individuals who do not comply with regularities. The frequency analysis on the first entry age of top-elite swimmers at the four performance levels showed an innovative method to describe the individual pathways toward acquisition of top-elite performance level. By analyzing these individual pathways, we gathered insight into the mean age and general age ranges at which top-elite swimmers for the first time started to perform at high-competitive, sub-elite, elite, and top-elite level. Consequently, the results demarcate age categories in which high-competitive, sub-elite, elite level have been achieved in order to successfully continue toward top-elite level.

From this study, we draw two conclusions. First, the results mark the important developmental stages of male and female top-elite swimmers by comparing their general level of performance with other performance groups. Top-elite swimmers are characterized by a high-performance level from 12 years on and progressively outperform swimmers from similar age. However, this goes together with a large variety in the individual pathways toward top-elite level within and between sexes. Second, at a methodological level, the present study successfully applied the method of Stoter and colleagues[22] and introduced an additional analysis that provided detailed insight about the age at which high-competitive, sub-elite, elite level was reached in order to make it to top-elite level in competitive swimming. This has the potential to be applied in other time-trial sports.

5 | PERSPECTIVE

The present study provides highly relevant and valuable information about the 100 m freestyle performance development of male and female top-elite swimmers. The general developmental patterns and the first entry ages per performance level of male and female top-elite swimmers may function as guideline for coaches with athletes who are aiming to reach the top. With the results of this study, swimmers and coaches may get a better indication about which performance level at a certain age-range seems to be required to develop toward top-elite level. This may help swimmers and coaches in monitoring swim performance and setting realistic short and long-term goals. The paramount differences within and between the performance development of male and female top-elite swimmers underline the importance of a personalized approach and may have important implications on future training and athlete development programs. A next step to take is to longitudinally study the underlying performance and environmental characteristics leading to top-elite swim performance.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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